Validation of K-XRF Bone Lead Measurement in Young Adults

Jane A. Hoppin,[1,2] Antonio C.A. Aro,[3] Paige L. Williams,[4] Howard Hu,[1,3] and P. Barry Ryan[1]

[1]Department of Environmental Health and [2]Department of Epidemiology, Harvard School of Public Health, Boston, MA 02115 USA; [3]Channing Laboratory, Department of Medicine, Brigham and Women's Hospital, Harvard Medical School, Boston, MA 02115 USA; [4]Department of Biostatistics, Harvard School of Public Health, Boston, MA 02115 USA

K-X-ray fluorescence (K-XRF) is a useful tool for assessing environmental exposure to lead in occupationally exposed individuals and older adults. This study explores the possibility of using this technique on young adults with low environmental lead exposure. Twenty-three college students, aged 18–21 years, were recruited for 2 hr of bone lead measurement. Bone lead measurements were taken from the mid-shaft tibia for periods of 30 or 60 min. In the analysis, 30-min measurements were combined so that each subject had the equivalent of two 60-min measurements. The average concentration of two bone lead measurements in this population ranged from -1.5 to 8.2 μg Pb/g bone mineral, with a mean of 3.0 μg Pb/g bone mineral. In a one sample *t*-test, this mean was significantly different from 0 ($p<0.0001$). A linear trend with age was detected despite the small age range of our population. By doubling the sampling time, the reported measurement uncertainty decreased by a factor of 1.5, resulting in uncertainty estimates below the mean bone lead estimates. Power calculations using the observed variance estimates suggest that with 80% power, differences in bone lead concentration of 2–3 μg Pb/g bone mineral can be identified in groups of 100 or smaller. Due to the large within-person variation in young adults, K-XRF may not yet be a useful diagnostic tool for individual subjects, but it may be of great use to environmental scientists trying to characterize long-term lead exposure and dose in the general population or specific subpopulations. *Key words:* bone lead measurement, lead, young adult lead exposure. *Environ Health Perspect* 103:78–83 (1995)

Lead is a ubiquitous contaminant in our environment. Lead is found in the food we eat, the air we breathe, and the water we drink. Even though recent regulations have reduced the current input of lead into the environment, lead persists in paint, soils, dust, and plumbing in homes, schools, and neighborhoods.

Lead is a xenobiotic, but it is found in measurable levels in all individuals. Lead concentration in blood is the most commonly used biological marker of lead exposure. Recent exposure to lead can be detected by changes in blood lead concentration; the half-life of lead in blood is estimated to be approximately 35 days (*1*). Chronic exposure to lead results in long-term storage of lead in bone; in adults, 95% of the body burden of lead is in bone (*2,3*). Autopsy studies suggest that the concentration of lead in bone increases with age and that bone lead represents a lifetime integrated measure of lead exposure (*1*). Bone lead may serve as a reservoir for lifetime lead exposure.

Over time, lead has been demonstrated to have effects in humans at progressively lower levels. Long-term developmental deficits in children have been demonstrated in longitudinal studies at blood lead levels less than 10–15 μg lead/dl blood (*4,5*), and meta-analysis failed to identify a threshold below which no effects are found (*6,7*). Similarly low levels of blood lead have been associated with elevations in blood pressure in adults in both longitudinal and cross-sectional investigations (*8–10*).

Until recently, measurements of lead burden in bone could only be taken at autopsy or using a needle biopsy. With the advent of K-X-ray fluorescence (K-XRF) technology, bone lead levels can be measured in a noninvasive manner (*11,12*). K-XRF analysis has been used to measure bone lead in a variety of occupationally and nonoccupationally exposed individuals (*12–15*). However, a recent National Academy of Sciences report (*16*) expressed concern about the usefulness of K-XRF technology in measuring bone lead levels in nonoccupationally exposed adults due to the potential for poor sensitivity at low lead concentrations. Bellinger et al. (*17*) cited a need for further improvements in the precision of K-XRF to establish bone lead as a useful biological marker of childhood lead absorption.

During the past 2 years, K-XRF technology has been improved to increase the sensitivity of the measurement. Aro et al. (*18*) demonstrated the consistency of K-XRF results with atomic absorption measurements for lead in standards of known lead concentration. Gordon et al. (*19*) recently demonstrated the reproducibility of bone lead measurements *in vitro* and in a small sample of human subjects. The current study focuses on issues concerning the K-XRF *in vivo* limit of detection and feasibility of measuring bone lead concentrations in young adults.

Methods

Volunteers were recruited from Boston-area universities. All subjects were between the ages of 18 and 21 years and had no known occupational lead exposure. All subjects were informed of the nature of the procedure before bone lead measurement.

We measured bone lead concentration in the left tibia of each subject using the K-XRF bone lead scanning apparatus developed by our research group. This apparatus has recently been redesigned to improve the sensitivity of bone lead measurement, thereby allowing for bone lead measurement in environmentally exposed individuals. The bone lead scanner operates on the principle of K-X-ray fluorescence. The technical specifications and the validation data are described in detail elsewhere (*18*). Briefly, the instrument uses a ^{109}Cd γ-ray source of activity 1.11 GBq and a high-purity germanium detector in a back-scatter geometry (*18*). The source-to-skin distance is approximately 2 cm. Gamma and X-ray signals are shaped and digitized and then acquired by a multichannel analyzer board in a personal computer. At the completion of the measurement time, the data are automatically stored for analysis. A schematic of this system is shown in Figure 1. In the ^{109}Cd K-XRF technique, lead X-rays are normalized to the elastic scatter peak; the elastic scatter peak is primarily due to elements of bone mineral rather than to those of human soft tissue (*20*). Normalization renders the accuracy of measurement relatively insensitive to variations in bone shape, size, and density; overlying skin thickness; and to minor subject movement (*20*). The precision of the measurement varies from person to person and depends primarily on the thickness of overlying tissue and the mass of bone mineral sampled. The presence of sufficient bone mass is critical in determining the lower age limit for bone lead measurement.

An estimate of measurement uncertainty accompanies each bone lead mea-

Address correspondence to J. A. Hoppin, Department of Environmental Health, Harvard School of Public Health, Building I, Room B21, 665 Huntington Avenue, Boston, MA 02115 USA.

This work was supported by NIEHS Superfund P42-ES05947 and NIEHS NRSA-5 T32 ES07069. Thanks to Ronda Appelbaum for subject recruitment, Michael Oh and Arif Shahabuddin for bone lead measurement, and to the research subjects. Special thanks to David Bellinger and Herbert Needleman for use of their bone lead data set.

Received 1 August 1994; accepted 14 October 1994.

surement made by K-XRF (for example, a tibia lead measurement may read 15.5 ± 3.2 μg/g bone mineral). The estimate of measurement uncertainty represents an estimate of the standard deviation of multiple measurements and is derived by a goodness-of-fit calculation of the scatter in the XRF spectrum. In experiments on a cadaveric leg in which we took serial measurements at multiple bone sites, these estimates of measurement uncertainty closely corresponded to the standard deviations derived from repeated measurements; however, Gordon et al. (*19*) estimated that the reported uncertainty underestimates the measurement variability by 20–30%.

Concentrations of lead reported from K-XRF measurements using this K-XRF instrument show good agreement with lead concentrations measured using inductively coupled plasma mass spectrometry (ICP-MS) across a wide concentration range (*18*). Calibration standards ranging from 0 to 114 μg Pb/g bone mineral were prepared using plaster of paris and known lead concentrations; these standards were then analyzed multiple times by both K-XRF and ICP-MS. The correlation between K-XRF and ICP-MS measurements was good (R^2 = 0.9998), with a slope close to unity (β = 0.9968), demonstrating that the K-XRF instrument has a linear relationship with lead concentration over the calibration range.

The effective radiation dose to the subject during an *in vivo* K-XRF measurement is very low and can be compared to natural background radiation (*21*). Todd et al. (*21*) describes in detail the radiation dosimetry studies involving similar K-XRF instruments. We calculated the effective doses using the new International Commission on Radiological Protection (*22*) recommendations. According to these results, the effective dose from a single K-XRF measurement of tibia is 0.2% and 0.1% of the average effective dose from a dental and chest X-ray, respectively. Similar dosimetry investigations of our apparatus have demonstrated even lower exposures, since the source strength is approximately half the strength of Todd's apparatus (2.2 versus 1.08 GBq). For our bone lead scanner, the estimated effective dose for a 60-min measurement of a 15-year-old subject is less than 190 nSv (*21*).

For this pilot study, subjects came to our K-XRF testing laboratory located in the Brigham and Women's Hospital in Boston, Massachusetts. Once at the facility, the procedure was reviewed. All subjects were asked about the presence of metal pins in either lower leg. If metal was not present in the lower leg, subjects were seated in a plastic resin chair, and the lower leg was restrained with Velcro straps to minimize movement during measurement. The measurement location of the mid-shaft of the left tibia was verified throughout the procedure by the technician.

To remove extraneous sources of lead from contaminating the measurement, the measurement location was washed with a 50% solution of isopropyl alcohol before sample collection. The test room was cleaned each day with a HEPA-filtered vacuum cleaner. After shielding the measurement area with lead-free steel walls, the area was monitored to determine that there was no background lead contamination that could affect sample results.

Bone lead measurements were taken from the mid-shaft of the left tibia for periods of 30 or 60 min. Here and throughout this paper, times refer to real or clock time, rather than instrumental live time. The collimator was positioned perpendicular to and in the middle of the anterior tibial surface. All measurements were collected at the same bone location over a 2-hr period. Subjects were allowed to move between measurements. During the sample collection time, subjects completed exposure history questionnaires, read magazines, and listened to music. Technicians were present at all times during the measurement to answer questions.

Each subject was measured for a total of 2 hr. In 14 subjects, 4 30-min measurements were taken; in 7 subjects, 2 60-min measurements were taken; and in 2 subjects 1 60-min and 2 30-min measurements were taken. For analytical purposes, we combined 2 consecutive 30-min measurements so that each subject had the equivalent of 2 60-min measurements.

Two bone lead concentrations were calculated for each subject using the stored lead spectra; these represent two 60-min repeat measurements. For individuals initially assessed by 30-min measurements, spectra from two consecutive 30-min measurements were combined and then analyzed as one complete 60-min measurement. The lead K-X-ray peaks were extracted from the spectrum using the nonlinear least-square fitting technique (*23*) with special fitting functions developed by the Birmingham University Group (*20*). The fitting software generates the K-X-ray to elastic ratio for each of the K-series X-rays. Since some of the K-series X-rays have greater variability than others, the final lead concentration was calculated from the means of the α_1, α_2, β_1, and β_3 peaks weighted by the inverse of their respective variances. Figure 2 illustrates the location of the α_1, α_2, β_1, and β_3 peaks in a 114 μg Pb/g bone mineral lead standard. The contributions of the different K-X-rays to overall precision are discussed elsewhere (*20*).

The fitting algorithm requires subtracting a fitted background curve from the actual data collected. Due to the statistical nature of the counting procedure, it is possible, especially for very low lead concentrations, that the value determined by subtracting the fitted background curve from the observed data is less than zero. This results in a negative value for the measured concentration. Negative values are not discarded; they represent the best estimate of the lead concentration for the individual and are thus useful in establishing the shape of the concentration distribution and in establishing the relative position of an individual's bone lead concentration within the population.

We performed statistical analyses to investigate whether bone lead concentration was measurable in young adults and to investigate to what extent bone lead measurements were reproducible in this age group. One-sample tests, correlation

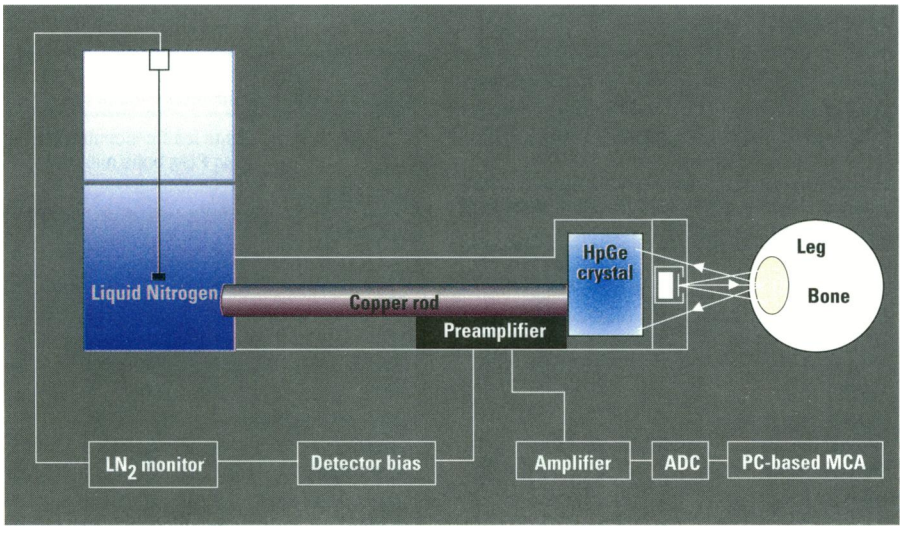

Figure 1. Schematic of bone lead scanner. HpGe, high-purity germanium detector; LN_2, liquid nitrogen; ADC, analog-digital converter; MCA, multichannel analyzer.

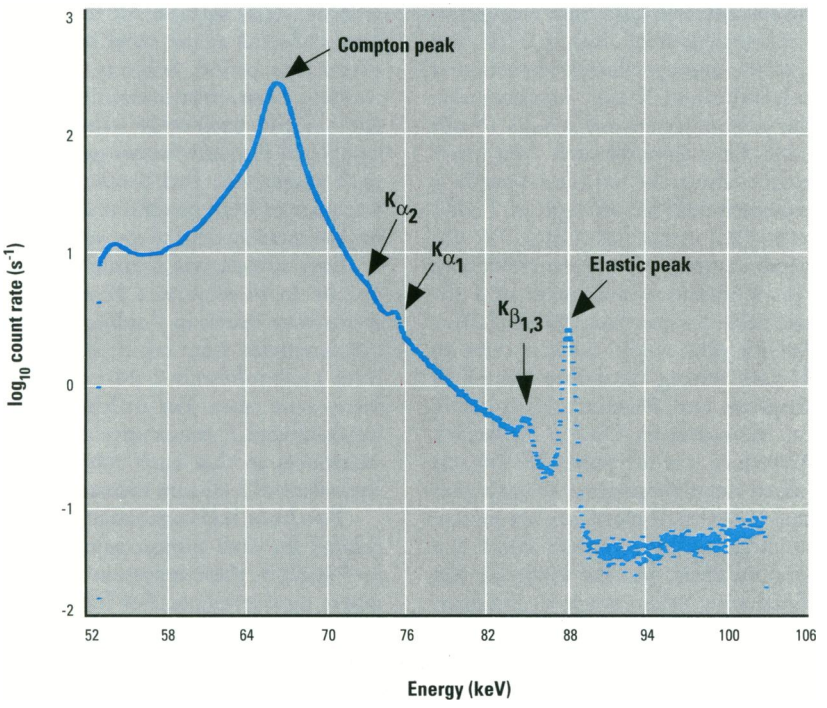

Figure 2. Typical K-XRF spectrum for a 117 µg Pb/g bone mineral lead standard.

analysis, and repeated-measures techniques were employed to address these issues. Additionally, the role of age on bone lead concentration was explored using regression analysis. All statistical analyses were carried out using the statistical packages STATA 3.1 (*24*) and SAS 6.09 (*25*).

The statistical analyses were conducted using two 60-min measurements per individual. Correlation analysis and repeated-measures models used the two samples per subject. For most of the analyses, the mean of these two measurements was used; these analyses included *t*-tests and linear regression. This average value was used, rather than creating one 120-min measurement, because a 60-min measurement time is viewed as the longest feasible measurement time in young subjects. Use of this measure helped provide more stable estimates of a subject's bone lead concentration.

For regression analyses, bone lead data were weighted based on the reported estimates of uncertainty. Each observation was weighted by the inverse of the squared measurement error using the following equation:

$$\mathrm{Var}(X) = \mathrm{Var}[(x_1+x_2)/2]$$
$$= 0.25[\mathrm{Var}(x_1)+\mathrm{Var}(x_2) - 2\,[\mathrm{cov}(x_1,x_2)]],$$

where X = mean of two 60-min measurements; x_1 = first 60-min measurement; x_2 = second 60-min measurement; and $\mathrm{cov}(x_1,x_2)$ = covariance between x_1 and x_2.

The variance for each of the two measurements, x_1 and x_2, was the squared measurement error for that observation; a constant covariance estimated empirically from the observed data was assumed for all pairs of measurements.

Results

Twenty-three subjects aged 18–21 years were recruited for this study; the average age of population was 19.3 years. A variety of racial groups were represented by the study subjects. Table 1 presents subject characteristics.

From Poisson counting statistics, doubling the sampling time should result in a decrease in the measurement uncertainty by a factor of $\sqrt{2}$ (*26*). In this sample, the increase in the sampling time resulted in an average reduction in measurement uncertainty by a factor of 1.5. The reduction in uncertainty provided a more accurate measurement of the lead concentration and allowed for the detection of mean concentrations not equal to zero. The decrease in measurement uncertainty resulted in reported measurement uncertainty within or below the range of the measured bone lead concentration. Based on the uncertainty measurements, the combination of the two 30-min measurements does not appear to be different from the complete 60-min measurements. Mathematically, these are equivalent measurements; statistical analysis, using linear regression models which contained a dummy variable for combined measurements, confirmed that there was no difference between the combined 30-min measurements and the 60-min measurements.

The bone lead concentration in this population is low compared to occupationally exposed subjects. The average of the two 60-min measures ranged from -1.5 to 8.2 µg Pb/g bone mineral, with a sample mean and standard deviation of 3.0 µg Pb/g bone mineral and 2.3 µg Pb/g bone mineral, respectively. Figure 3 presents a histogram of the average bone lead concentrations. The reported measurement error associated with these 60-min estimates ranged from 2.4 to 4.8 µg Pb/g bone mineral, with a mean and standard deviation of 3.3 and 0.55 µg Pb/g bone mineral, respectively. A one–sample *t*-test was used to test the hypothesis that the mean of the

Table 1. Population characteristics: number of subjects in each category

Characteristic	Age, years 18	19	20	*N*
Sex				
Female	7	8	3	18
Male	2	2	1	5
Race (self-reported)				
White	6	7	2	15
All nonwhites	3	3	2	8
African-American	0	1	1	2
Haitian	0	1	0	1
Hispanic	2	1	1	4
Native American	1	0	0	1

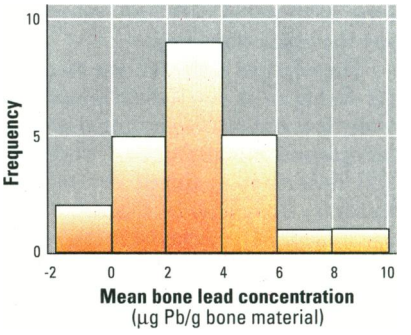

Figure 3. Distribution of bone lead concentration.

Table 2. Distribution of bone lead by age, sex, and race: number of subjects in each category

Characteristic	Bone lead concentration (µg Pb/g bone mineral) <1	1–4	>4	*N*
Age, years				
18	4	5	0	9
19	2	4	4	10
20	0	1	3	4
Sex				
Female	4	9	5	18
Male	2	1	2	5
Race (self-reported)				
White	4	8	3	15
All nonwhites	2	2	4	8
African-American	0	0	2	2
Haitian	0	1	0	1
Hispanic	1	1	2	4
Native American	1	0	0	1

observed bone lead distribution does not differ from zero. This test indicated that this hypothesis could be rejected ($p<0.0001$), suggesting that bone lead is measurable in young adults using this technique. Table 2 presents the bone lead distribution by age, sex, and race.

We used a variety of statistical methods to evaluate the reproducibility of these bone lead measurements. Using a paired t-test, no difference between the means of the two measurements was observed. The observed Pearson correlation between the two 60-min measurements was not significantly different from zero (p = 0.3324); nonparametric measures of correlation showed similar results. These results suggest that bone lead measurements for a population with very low lead exposure are reproducible; however, it may be due to the small size of the sample. Reproducibility results for individuals are not as convincing. Analysis of variance techniques were used to determine whether individuals could be distinguished on the basis of their bone lead results. Due to the large within-person variance (approximately twice the between-person variance), subjects cannot be differentiated on the basis of two bone lead measurements. This may be due to the limited range of lead concentration in this population. Implications of this finding on sample size and power will be discussed further.

An interesting unanticipated finding was the demonstration of an effect of age on bone lead concentration. Even given the small age range, a statistically significant increase of 1.5 µg Pb/g bone mineral Pb per year (p = 0.0065) was estimated using linear regression analysis based on the average of the two 60-min measurements; the intercept for this model is -25.8 µg Pb/g bone mineral Pb. Age may be considered to represent duration of environmental exposure and not aging per se. The R^2 for this model was 0.3033, indicating that age explained 30% of the variance in bone lead concentration in a population generally thought to be identical with respect to age. The unweighted regression model gave qualitatively similar results, with an R^2 of 0.2981. Figure 4 presents the weighted regression model for bone lead and age. Regression diagnostics were performed to evaluate the model; no outliers were identified.

To take advantage of the presence of the duplicate measures of bone lead and to account for the correlation between the measures, two types of repeated-measure models were employed. Due to software constraints, the measurements of bone lead were not weighted for measurement uncertainty. A multivariate analysis of variance model (MANOVA) used both of the 60-min measurements for each subject as dependent variables with age as the independent variable; this model demonstrated a statistically significant effect of age on the two measures (p = 0.0174). A repeated-measures analysis of variance did not demonstrate an effect of measurement order (p = 0.7372); the age effect was significant (p = 0.0070). These results suggest that even in the presence of measurement error, age plays a significant role in the prediction of bone lead concentration.

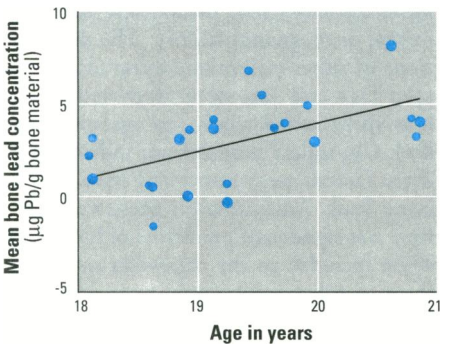

Figure 4. Scatter plot and weighted regression line of tibia bone lead level versus age in 23 adolescents. Size of the diameter of each point is proportional to the inverse of the estimate of uncertainty for the bone-XRF measurement (the smaller the point, the larger the estimated measurement uncertainty). Univariate regression of bone lead on age was $Y = 1.5\,X - 25.8$, where Y = tibia bone lead concentration (µg/g bone mineral), and X = age (years); $R^2 = 0.3033$.

Discussion

The results of this study indicate the feasibility of using K-XRF technology to investigate bone lead in young adults. In particular, we have demonstrated the ability of this technique to detect lead in bones of young, nonoccupationally exposed subjects. Further, we have shown that trends in bone lead concentration with age can be discerned.

The average bone lead concentrations measured here, ranging from -1.5 to 8.2 µg Pb/g bone mineral, are consistent with those seen in young adults by other investigators. For example, in a follow-up study of 18–22 year olds of the original Needleman (*27,28*) cohort, Bellinger et al. (*17*) found tibial lead concentrations ranging from -9 to 19 µg Pb/g bone mineral, with a sample mean and standard deviation of 1.6 and 4.9 µg Pb/g bone mineral, respectively. These were collected over a 30-min time period using a less sensitive K-XRF apparatus. In a community-based study of 101 individuals aged 11–70 years using a half-hour measurement time, Kosnett et al. (*29*) reported a mean tibial bone lead concentration of 12.7 µg Pb/g bone mineral with a range of -12 to 69 µg Pb/g bone mineral for the entire population; for the 14 individuals less than 20 years of age, the mean bone lead concentration was not different from zero.

These results are also consistent with results from cadaver studies. Cadaver studies supply highly accurate data because samples can be analyzed multiple times by atomic absorption spectroscopy (AAS). Post-mortem studies are useful for comparison purposes but are not feasible for the longitudinal measurement of bone lead concentrations in humans. In a post-mortem study by Wittmers et al. (*30*) of 13 subjects aged 13–20 years, the average bone lead concentration was 2.3 µg Pb/g bone ash, with a standard deviation of 3.6. In a study of five children 11–16 years old in England, Barry (*31*) reported an average tibial bone lead concentration of 2.68 µg Pb/g bone mineral (wet weight), with a standard deviation of 1.06; the ashed weight equivalent for this value is 4.8 µg Pb/g bone mineral. These results are consistent with our mean bone lead concentration of 3.0 µg Pb/g bone mineral.

As expected, the concentrations of tibial bone lead in this young adult population were much lower than both occupationally exposed and nonexposed adult populations. In a study conducted in Finland, Erkkila et al. (*32*) reported average bone lead concentrations of 21.1 µg Pb/g bone mineral, 32.4 µg Pb/g bone mineral, 7.7 µg Pb/g bone mineral, and 3.5 µg Pb/g bone mineral for current lead workers with an average exposure duration of 12 years, former lead workers with an average exposure duration of 15 years, office workers in the lead factory, and unexposed control workers, respectively. Somervaille et al. (*33*) reported tibial bone lead concentrations ranging from an average of 16.7 µg Pb/g bone mineral for nonexposed workers to 54.8 µg Pb/g bone mineral for lead factory workers.

With the improvement in measurement sensitivity, we were able to detect an age-related increase in bone lead that has not been seen by other investigators studying this age group (*17,29*). Cross-sectional studies in adults using less sensitive equipment (*29,34*) have demonstrated age-related increases in bone lead concentration beginning at approximately age 20. Further analysis of the bone lead measurements on the Needleman cohort (*17*) indicates some interesting findings that may merit further investigation. In the whole population of 67 subjects, the unweighted regression model for age as a predictor of tibial bone lead concentration was not significant (p = 0.3386, R^2 = 0.0139); however, when the reported bone lead concentrations were weighted by their reported measurement uncertainty, a regression coefficient of 1.04 µg Pb/g bone mineral Pb per year (SE = 0.637, p = 0.1064, R^2 = 0.039)

was observed. When the analysis was limited to the 51 subjects aged 18–21 years, an unweighted regression coefficient of 1.53 µg Pb/g bone mineral Pb per year was observed (SE = 0.9127, p = 0.0997, R^2 = 0.0544); when the model was weighted for measurement error, the parameter estimate was 1.75 µg Pb/g bone mineral Pb per year (SE = 0.7582), with a p-value of 0.0247 and an R^2 for the model of 0.0987. While the R^2 values for these models are not suggestive of an important explanatory effect of age, the parameter estimates of the slope are similar to that observed in this investigation (β = 1.5); this suggests that by increasing the sensitivity of bone lead measurement, predictive models of bone lead concentration may be developed for young adults. Through the improvement in the sensitivity of the K-XRF apparatus, we are able to explain over 30% of the variation in bone lead concentration as a function of age over a very small age range with a small sample size (n = 23).

In studies of occupationally and nonoccupationally exposed adults, other investigators have found an average increase in bone lead concentration ranging from 0.38 to 0.41 µg lead per year (*29,34–36*); the ages in these studies have ranged from 20 to 70 years. In both this study's data and the Needleman cohort data, an average increase of approximately 1.5 µg lead per year was seen over a 3-year age range. The 95% confidence interval for the predicted slope in our study (0.46, 2.5) excludes the values seen for older adults. It should be noted that all these studies are cross-sectional, and the observed change with age may have a variety of explanations; longitudinal studies are necessary to distinguish the effects of secular trends in environmental lead exposure from bone lead kinetics in producing the observed change.

If the model correctly predicts the trend of bone lead with age, then bone lead concentrations should be measurable in those subjects aged 18 years and older, and, conversely, measuring bone lead in subjects less than 18 years old may be difficult. However, due to the small sample size and the model uncertainty, extrapolating past the range of the observed data should be done cautiously.

Since this is a pilot study focusing on the ability to measure bone lead concentration, little effort was made to collect complete information on potential confounders which may alter the observed association between age and bone lead. Data were collected on housing characteristics, history of lead poisoning, cigarette smoking, and occupation and hobbies which may contribute to lead exposure; the population was relatively homogeneous with respect to these exposures. No information was collected on body size, dietary and drinking habits, or pregnancy history. The distributions of other potential confounding factors, race and sex, were examined to see how these varied relative to age and bone lead. Chi-square tests did not indicate that these factors were associated with age or bone lead. Additionally, these variables were not significant predictors of bone lead when included in the regression model. If these or other factors were responsible for increasing sample variability, then it is unlikely that we would be able to show a statistically significant effect of age, given the small sample size. Other investigators (*29,34–36*) have demonstrated that age is the most important predictor of bone lead concentration; this study suggests that all models predicting bone lead should include age in the model regardless of the age range in the sample. Sex is not anticipated to be a confounder in this age range; Kosnett et al. (*29*) found an effect of sex only in subjects greater than 55 years of age. Larger studies over a small age range are needed to investigate other factors associated with lead storage in bone.

Even with current technological improvements, there still is substantial measurement uncertainty due to the small amount of lead, incomplete bone mineralization, and technological limitations. However, power calculations based on a two-sample t-test indicate that, even in the presence of measurement error, a difference of 2–3 µg Pb/g bone mineral lead can be detected with 80% power with sample sizes as small as 50 people per group. Due to the relatively large variability within a subject at low lead concentrations, K-XRF currently would not be a good diagnostic tool among individuals exposed to lower levels of lead. For populations, however, repeated measurements over time can be used to investigate lead kinetics in bone.

One key observation from this pilot study is the imperative to keep and maintain a lead-free environment in the measurement facility. Prior to study start-up, we experienced difficulties due to lead paint on walls, lead in cinder block behind walls, and lead in aluminum wrappers for alcohol swabs. Since the concentrations of interest are at the low part-per-million level, these and other potential lead sources may bias results if they are not addressed before sample collection.

K-XRF is a useful tool for environmental epidemiological investigations of bone lead concentration in young adults. By reconfiguring the apparatus, increasing the measurement time, and maintaining a lead-free measurement environment, we were able to detect measurable levels of lead in the bones of young adults. Because bone lead concentrations can be assessed in such a young population, longitudinal studies can be used to investigate factors associated with age as predictors for bone lead concentration. By evaluating environmental factors and the concomitant increase or decrease in bone lead concentrations, models can be developed for uptake of lead to bones from blood and, ultimately, from the environment.

References

1. Rabinowitz MB. Toxicokinetics of bone lead. Environ Health Perspect 89:95–100 (1990).
2. Schroeder H, Tipton I. The human body burden of lead. Arch Environ Health 17:965–978 (1968).
3. Barry PSI, Mossman D. Lead concentration in human tissues. Br J Ind Med 27:339–351 (1970).
4. Bellinger D, Sloman J, Leviton A, Rabinowitz M, and Needleman HL, Waternaux C. Low-level lead exposure and children's cognitive function in the preschool years. Pediatrics 87:219–227 (1991).
5. Baghurst PA, McMichael AJ, Wigg NR, Vimpani GV, Robertson EF, Roberts RJ, Tong SL. Environmental exposure to lead and children's intelligence at the age of seven years. N Engl J Med 327:1279–1284 (1992).
6. Schwartz J. Low-level lead exposure and children's IQ: a meta-analysis and search for a threshold. Environ Res 65:42–55 (1994).
7. Needleman HL, Gatsonis CA. Low-level lead exposure and the IQ of children. J Am Med Assoc 263:673–678 (1990).
8. Schwartz J. The relationship between blood lead and blood pressure in NHANES II survey. Environ Health Perspect 78:15–22 (1988).
9. Sharp DS, Benowitz NL, Osterloh JD, Becker CE, Smith AH, Syme SL. Influence of race, tobacco use, and caffeine use on the relation between blood pressure and blood lead concentration. Am J Epidemiol 131:845–854 (1990).
10. Sorel JE, Heiss G, Tyroler HA, Davis WB, Wing SB, Ragland DR. Black-white differences in blood pressure among participants in NHANES II: the contribution of blood lead. Epidemiology 2:348–352 (1991).
11. Landrigan PJ. Strategies for epidemiologic studies of lead in bone for occupationally exposed populations. Environ Health Perspect 91:81–86 (1991).
12. Landrigan PJ, Todd AC. Direct measurement of lead in bone: a promising biomarker. J Am Med Assoc 271:239–240 (1994).
13. Hu H, Milder FL, Burger DE. X-Ray fluorescence: issues surrounding the application of a new tool for measuring lead burden. Environ Res 49:295–317 (1989).
14. Todd AC, McNeill FE, Fowler BA. In vivo X-ray fluorescence of lead in bone. Environ Res 59:326–335 (1992).
15. Hu H, Aro ACA, Rotnitsky A. Bone lead measured by X-ray fluorescence: epidemiologic methods. Environ Health Perspect Suppl 102(11): in press.
16. National Academy of Sciences. Measuring lead exposure in infants, children, and other sensitive populations. Washington, DC:National Academy Press, 1993.
17. Bellinger D, Hu H, Titlebaum L, Needleman H. Attentional correlates of dentin and bone lead levels in adolescents. Arch Environ Health 49:98–105 (1994).

18. Aro ACA, Todd AC, Amarasiriwardena C, Hu H. Improvements in the calibration of ^{109}Cd K X-ray fluorescence systems for measuring bone lead in vivo. Phys Med Biol 39 (in press).
19. Gordon CL, Webber CE, Chettle DR. The reproducibility of ^{109}Cd-based X-ray fluorescence measurements of bone lead. Environ Health Perspect 102:690–694 (1994).
20. Chettle DR, Scott MC, Somervaille LJ. Lead in bone: sampling and quantitation using K X-rays excited by ^{109}Cd. Environ Health Perspect 91:49–55 (1991).
21. Todd AC, McNeill FE, Palethorpe JE, Peach DE, Chettle DR, Tobin MJ, Strosko SJ, Rosen JC. In vivo X-ray fluorescence of lead in bone using K X-ray excitation with ^{109}Cd sources: radiation dosimetry studies. Environ Res 57:117–132 (1992).
22. International Commission on Radiological Protection. 1990 Recommendations of the International Commission on Radiological Protection. Ann ICRP 21:1–3 (1991).
23. Marquardt DW. An algorithm for least squares estimation of nonlinear parameters. J Soc Ind Appl Math 11:431–441 (1963).
24. Stata Corporation. Stata reference manual: release 3.1, 6th ed. College Station, TX:Stata Corporation, 1993.
25. SAS Institute Inc. SAS user's guide: statistics, 6th ed. Cary, NC:SAS Institute, 1991.
26. Shapiro J. Radiation protection: a guide for scientists and physicians, 3rd ed. Cambridge, MA:Harvard University Press, 1990.
27. Needleman HL, Gunnoe C, Leviton A, Reed R, Peresie H, Maher C, Barrett P. Deficits in psychologic and classroom performance of children with elevated dentine lead levels. N Engl J Med 300:689–695 (1979).
28. Needleman HL, Schell A, Bellinger D, Leviton A, Allred EN. The long-term effects of exposure to low doses of lead in childhood: an 11-year follow-up report. N Engl J Med. 322:83–88 (1990).
29. Kosnett MJ, Becker CE, Osterloh JD, Kelly TJ, Pasta DJ. Factors influencing bone lead concentration in a suburban community assessed by noninvasive K X-ray fluorescence. J Am Med Assoc 271:197–203 (1994).
30. Wittmers LE, Wallgren J, Alich A, Aufderheide AC, Rapp G. Lead in bone. IV. distribution of lead in the human skeleton. Arch Environ Health 43:381–391 (1988).
31. Barry PSI. Concentrations of lead in the tissues of children. Br J Ind Med 38:61–71 (1981).
32. Erkkila J, Armstrong R, Riihimaki V, Chettle DR, Paakkari A, Scott M, Somervaille L, Starck J, Kock B, Aitio A. In vivo measurements of lead in bone at four anatomical sites: long term occupational and consequent endogenous exposure. Br J Ind Med 49: 631–644 (1992).
33. Somervaille LJ, Chettle DR, Scott MC, Tennant DR, McKiernan MJ, Skilbeck A, Trethowan WN. In vivo tibia lead measurements as an index of cumulative exposure in occupationally exposed subjects. Br J Ind Med 45:174–181 (1988).
34. Hu H, Milder FL, Burger DE. X-ray fluorescence measurements of lead burden in subjects with low-level community lead exposure. Arch Environ Health 45:335–341 (1990).
35. Somervaille LJ, Chettle DR, Scott MC, Aufderheide AC, Wallgren JE, Wittmers LE Jr, Rapp GR Jr. Comparison of two in vitro methods of bone lead analysis and the implications for in vivo measurements. Phys Med Biol 31:1267–1274 (1986).
36. Watanabe H, Hu H, Rotnitsky A. Correlates of bone and blood lead levels in carpenters. Am J Ind Med 26:255–264 (1994).